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OPTICAL AND LONG WAVELENGTH AFTERGLOW FROM GAMMA-RAY BURSTS

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ABSTRACT

We discuss the evolution of cosmological gamma-ray burst remnants, consisting of the cooling and expanding fireball ejecta together with any swept-up external matter, after the gamma-ray event. We show that significant optical emission is predicted which should be measurable for timescales of hours after the event, and in some cases radio emission may be expected days to weeks after the event. The flux at optical, X-ray and other long wavelengths decays as a power of time, and the initial value of the flux or magnitude, as well as the value of the time-decay exponent, should help to distinguish between possible types of dissipative fireball models.

Subject headings: gamma rays: bursts

1. Introduction

Gamma-Ray Bursts (GRB) must leave behind remnants, hereafter referred to as GRBR. In general, GRB at any plausible distance should result in relativistically expanding fireballs (e.g. Mészáros, 1995 for a review), and the γ-ray emission most probably arises after the fireball becomes optically thin, in shocks occuring either beacuse the ejecta run into an external medium, or because internal shocks occur in a relativistic wind. In the first type (a) of GRB model, the initial energy input is impulsive and the relativistic ejecta begin to decelerate when they have swept up external mass that is a fraction $\sim \Gamma^{-1}$ of the ejecta mass, leading to an external and a reverse shock that radiate a large fraction of the initial total energy (the GRB event, Rees &

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Mészáros, 1992, Mészáros & Rees, 1993a, Katz, 1994, Sari, Narayan & Piran, 1996). However, after this initial burst the ejecta should still continue to expand, sweeping up an increasing amount of matter and slowing down. As pointed out by Paczyński & Rhoads, 1993, the evolution of such an "old" cooling fireball should resemble the Van der Laan model of expanding radio sources, and they estimated the possibility of detecting the late radio emission from such objects. In the second type (b) of GRB model (Rees & Mészáros, 1994, Paczyński & Xu, 1994), the initial energy input continues over a period of time t_w and the resulting relativistic fireball wind produces a GRB due to internal shocks in the wind itself. These objects too should leave behind a cooling remnant, although the dynamics of the late evolution are expected to be different from those of type (a) because the burst occurs at significantly smaller radii and the effects of the external matter are negligible for some time afterwards so the dynamics are different.

In this paper we investigate the dynamical evolution of the GRBR following the GRB event, both for the impulsive external shock and the wind internal shock models. We assume that the GRB are at cosmological distances (similar models with somewhat different radiation characteristics can be calculated for galactic halo models too). Both types of cosmological GRBR produce, in addition to decaying γ-rays, significant amounts of softer radiation, mostly X-rays and optical, but in some cases also radio. Depending on the distance to the source, the duration of the main GRB event and the physics of the burst model, this radiation can be in many cases detectable with appropriate instrumentation. Based on practical considerations of sensitivity, telescope availability and fast response time, the best chances for detection at energies other than gamma-rays may be at optical wavelengths.

2. Dynamical Evolution of GRBR

A source at distance D expanding isotropically with a relativistic bulk Lorentz factor Γ, which in its own frame has a comoving specific intensity I'_{ν_m} at comoving frequencu ν'_m, will produce as a function of observer time t an observer-frame flux at frequency ν_m

$$F_{\nu_m} \sim \frac{c^2 t^2 \Gamma^2}{D^2} \Gamma^3 I'_{\nu_m}, \tag{1}$$

where $\nu_m = \Gamma \nu'_m$ and where the observed transverse apparent size $ct\Gamma$ is used (Rees, 1966). In the initial phase of expansion of the fireball the internal energy density drops adiabatically and most of the energy is locked up in the expansion kinetic energy, so that I'_{ν_m} is negligible until after shocks dissipate some or all of the bulk kinetic energy in the GRB event. At this point, the GRB spectrum is generally considered to be due to synchrotron or inverse Compton (IC) radiation from power-law electrons or pairs accelerated in the shocks. A break in the spectrum appears at photon energies associated either with synchrotron photons whose index changes below and above the minimum synchrotron frequency corresponding to electrons with γ_{min}, or else with IC photons corresponding to the same break but shifted up in energy by γ_{min}^2 (Mészáros, Rees & Papathanassiou, 1994, henceforth MRP94). If electrons have an energy distribution $\propto \gamma^{-3}$ above

γ_{min}, the νF_ν photon spectrum below the break is $\propto \nu^1$ (or $\nu^{4/3}$, but we shall take $\propto \nu^1$ as a generic observed spectrum), and is flat above that. The GRB spectral breaks which are detected by BATSE generally in the 0.1-2 MeV region, e.g. Band, etal., 1993 (although they could have a much broader distribution, Piran & Narayan, 1996), could be due to the synchrotron break (e.g. the PC model in RMP94, or Katz, 1994, Sari, Narayan & Piran, 1996). Alternatively, a synchrotron spectral break might appear at significantly lower frequencies, and the similarly shaped IC scattered spectrum could provide the MeV break (MRP94, models FC and TC). A key quantity therefore, both for the GRB and the ensuing GRBR, is the comoving synchrotron intensity at the comoving synchroton peak frequency $\nu'_m \sim 10^6 B' \gamma_{min}^2$Hz, where B' (G) is the comoving magnetic field strength,

$$I'_{\nu_m} \propto \frac{n'_e B'^2 \gamma_{min}^2 \Delta R'}{B' \gamma_{min}^2} \propto n'_e B' \Delta R' \ . \tag{2}$$

The GRB from impulsive fireball external shocks are expected to produce simultaneous X-ray and optical flashes (Mészáros & Rees, 1993b, MRP94) whose duration is similar to that of the gamma-ray burst. Continuous wind fireball shocks also produce flashes of softer radiation which are contemporaneous with the GRB flash (Papathanassiou & Mészáros, 1996). The relative amount of contemporaneous soft emission depends on the type of shocks, the particle acceleration process and the strength of the magnetic field in the acceleration region. For the GRBR, the shock physics is also a major input in determining the comoving intensity I'_{ν_m} (equation 1), and thus the relative amounts of soft emission expected *after* the main gamma-ray and contemporaneous X-ray/optical flash is over. To a very large extent, however, the temporal behavior of the GRBR will be dominated by the evolution of Γ and some of the related dynamic quantities, which are different depending on the initial energy input regime giving rise to the fireball.

a) In the impulsive model, the fireball initially expands at its saturation bulk Lorentz factor $\Gamma \sim \eta = (E_o/M_o c^2) \sim$ constant, and upon interaction with an external medium it develops a blast wave moving into the external medium and a reverse wave moving into the ejecta, which radiate away a substantial fraction of the initial energy E_o to give the GRB. This occurs at a relatively large radius $r_{dec} \sim 10^{16} (E_{51}/n_{ext})^{1/3} \eta_3^{-2/3}$cm over an observer-frame timescale $t_\gamma \sim t_{dec} \sim r_{dec} c^{-1} \Gamma^{-2} \sim 1\ (E_{51}/n_{ext})^{1/3} \eta_3^{-8/3}$s, which is in the range $1 - 10^3$s for $\eta_3 \sim 1 - 10^{-1}$ (this is the observer-frame burst duration, for an impulsive type of initial energy input occuring over a timescale shorter than t_{dec}). During the GRB the radiative timescales are short enough to ensure high radiative efficiency, but the initial rapid cooling is generally sufficient to ensure that the subsequent evolution of the remnant will be adiabatic. For such impulsive fireballs, if the external medium is approximately homogeneous, the GRBR will continue to evolve afterwards with

$$\Gamma \propto r^{-3/2} \propto t^{-3/8} \ \ ; \ \ r \sim ct\Gamma^2 \propto t^{1/4} \ . \tag{3}$$

Here Γ is the Lorentz factor of the contact discontinuity (CD) between ejecta and external medium, and essentially also that of the external shock, r is the distance advanced by the CD along the line of sight (longitudinal size), and t is observer-frame time. The comoving expansion

(adiabatic cooling) time is $t'_{ex} \sim rc^{-1}\Gamma^{-1} \propto t^{5/8}$, and the comoving radial extent of the shell of fireball and swept-up matter is $\Delta R' \sim ct'_{ex} \propto t^{5/8}$.

b) In the continuous input (wind) model, before the GRB the wind is expanding at its saturation average bulk Lorentz factor $\Gamma \sim \eta = (L/\dot{M}_o c^2) \sim$ constant, and the primary energy input remains continuous (rather than being impulsive) over a wind duration timescale t_w which characterizes the burst duration in the observer frame. Variations on a timescale $t_{var} < t_w$ of the bulk Lorentz factor $\Delta\Gamma \sim \Gamma$, e.g. due to corresponding L or $\dot{M}$ variations, lead to internal shocks at relatively smaller radii $r_{dis} \sim ct_{var}\Gamma^2 \sim 3 \times 10^{11} t_{var,-3}\eta_2^2$ cm, which randomize the relative kinetic energy of different shells of the wind and radiate away a fraction of order unity of the total wind kinetic energy (the GRB event; e.g. Rees & Mészáros, 1994, Paczyński & Xu, 1994, Waxman & Piran, 1994). During the shocks (for $t \lesssim t_w$) Γ does not change very much and may be taken as approximately constant. After the shocks cease ($t > t_w$), the wind remains at $\Gamma \sim \alpha\eta \sim$ constant (with $\alpha \lesssim 1 \sim$ constant) as long as deceleration by an external medium does not come into play. (If and when this occurs, an external shock should develop, leading to a slow motion version of an impulsive GRB; the remnant thereafter behaves similarly to to case (a) above). In the range $r_{dis} \lesssim r \lesssim r_{dec}$ (where $r_{dec} \sim 2 \times 10^{17}(E_{51}/n_{ext})^{1/3}\theta^{-2/3}\eta_2^{-2/3}$ cm is reached after a time $t_{dec} \sim 10^3(E_{51}/n_{ext})^{1/3}\theta^{-2/3}\eta_2^{-8/3}$s) the wind and the remnant evolve with

$$\Gamma \sim \alpha\eta \sim \text{constant} \;\; ; \;\; r \sim ct\Gamma^2 \propto t \;, \tag{4}$$

where as before r is the distance advanced by the CD (the front of the wind) in observer time t. During the wind regime and for $t \leq t_w$, while internal shocks continue producing the GRB light curve, the comoving density evolves as $n' \propto r^{-2} \propto t^{-2}$ and any comoving wind (transverse) field as $B' \propto r^{-1} \propto t^{-1}$. However, for $r \gtrsim r_{imp} \sim ct_w\Gamma^2 \sim 3 \times 10^{14} t_w \eta_2^2$ cm, or for times $t_w \lesssim t \lesssim t_{dec}$, the wind has stopped blowing while the flow can still have (temporarily at least) $\Gamma \sim$ constant and $r \propto t$. The flow is now in an impulsive regime (observer-frame durations are $\gtrsim t_w$), and the gas expands isotropically in its own rest frame. The very rapid cooling during the GRB again ensures that the subsequent evolution of the smoothed-out remnant wind is adiabatic. In this GRBR regime then $n'_e \propto r^{-3} \propto t^{-3}$, $B' \propto r^{-2} \propto t^{-2}$, and particle random Lorentz factors cool adiabatically as $\gamma \propto n'^{1/3} \propto r^{-1} \propto t^{-1}$.

3. GRBR Spectra from Impulsive Fireballs

One can think of three main sub-cases which share the impulsive external shock dynamics described in §2 (a), but which, depending on the type of shock physics involved lead to different GRBR spectral evolution regimes.

(a1) For the simplest impulsive model, only the forward blast wave radiates efficiently (e.g. the reverse shock might be an inefficient particle accelerator or an inefficient radiator; this might be the case if the reverse shock were very weak, perhaps due to a very high Alfvén sound speed). This corresponds to the PC (piston) impulsive GRB model described in RMP94, e.g. their

Figure 1c. As a specific example, this model has a γ-ray fluence $S_\nu \sim \nu F_\nu t_\gamma \sim 10^{-7} E_{51} \theta_{-1}^{-2} D_{28}^{-2}$ erg cm^{-2} near the BATSE threshold, where the total energy is $10^{51} E_{51}$ erg channeled into an angle $10^{-1}\theta_{-1}$ radians at a luminosity distance $10^{28} D_{28}$ cm (roughly 3 Gpc; the same object at 300 Mpc would give one of the brighter bursts). This GRB spectrum satisfies amply the X-ray paucity constraint ($L_x \ll 10^{-2} L_\gamma$), being due to synchrotron radiation that peaks at $E_{br} \sim 0.5 \eta_3 B' \gamma_{min}^2$ MeV, with a νF_ν slope near 1 below E_{br} and near 0 above it. The ν^1 behavior below the break extends during the GRB at least down to optical frequencies, but becomes self-absorbed well above the radio range. This spectrum would be expected from electrons with an energy power law index $p \sim 3$ above $\gamma_{min} \sim \kappa \Gamma \sim 10^5 \eta_3 \kappa_2$. Here $\eta = 10^3 \eta_3$ is the final coasting bulk Lorentz factor, $B' \sim 10$ G is the turbulently generated comoving magnetic field strenght and γ_{min} is the minimum post-shock electron random Lorentz factor, assuming that electrons and protons achieve a fraction $\kappa m_e/m_p$ of their equipartition energy (for details see MRP94). In the GRB event, the fireball loses on the order of its initial kinetic (total) energy, and we can assume adiabatic conditions for the GRBR evolution, i.e. the comoving cooling time rapidly becomes longer than the comoving expansion time. The comoving intensity (2) from the external matter that produced the initial GRB and which subsequently evolves adiabatically is $I'_{\nu_m} \propto t^{-5/4}$, since $B' \propto V'^{-2/3}$, $n'_e \propto V'^{-1} \propto t^{-9/8}$, $\gamma \propto r^{-1} \propto t^{-1/4}$. Therefore $F_{\nu_m} \propto t^2 \Gamma^5 I'_{\nu_m} \propto t^{-9/8}$ starts to decrease in time immediately after the GRB for this initially shocked shell of external matter, its peak frequency dropping as $\nu_m \propto \Gamma B' \gamma^2 \propto t^{-13/8}$, giving $F_{\nu_m} \propto \nu_m^{9/13}$. This adiabatically cooling leftover component from the GRB is, however, weaker than that due to newly shocked external matter, as the ejecta continues to advance at a steadily decreasing velocity into the external matter. For this newly shocked matter B', n'_e, γ are all three independently $\propto \Gamma \propto t^{-3/8}$, so $I'_{\nu_m} \propto t^{-1/8}$. As a result, from (1) the observed flux at the break evolves initially as $F_{\nu_m} \propto t^0 \sim$ constant, so the flux below the break remains constant, $F_\nu \propto \nu^0 \simeq$ constant as long as $\nu < \nu_m$, but the latter decreases in time as $\nu_m \propto t^{-3/2}$. If we take approximately the gamma-ray band to be at 10^{20} Hz and the optical band at 10^{15} Hz, ν_m drops below the optical band at $t_{opt} \sim 3 \times 10^3 t_\gamma$, where $t_\gamma \sim t_{dec}$ is the duration of the gamma-ray flash defined below equation (1). Thus, since the flux is $\propto \nu^{-1}$ above ν_m the detected *optical* flux from an impulsive (a1) type GRBR is $F_{opt} \sim 10^{-27} K\ D_{28}^{-2} =$ constant for $t \lesssim t_{opt} \sim 3 \times 10^3 t_\gamma$, and $F_{opt} \sim 10^{-27} K\ D_{28}^{-2} (t/t_{opt})^{-3/2}$ for $t \gtrsim t_{opt}$, where flux units are erg cm^{-2} s^{-1} Hz^{-1}, D is the luminosity distance and $K = E_{51} \theta_{-1}^{-2}$ is the burst energy normalization . The corresponding V-band magnitudes are $m_v = -2.5 \log(F_{opt}/4 \times 10^{-20})$ or

$$
\begin{aligned}
m_v &\simeq 19 - 2.5 \log K + 5 \log D_{28} \quad , \text{for } t \lesssim 3 \times 10^3 t_\gamma \ , \\
m_v &\simeq 19 - 2.5 \log K + 5 \log D_{28} + 3.75 \log(t/t_{opt}) \quad , \text{for } t \gtrsim 3 \times 10^3 t_\gamma \ ,
\end{aligned}
\tag{5}
$$

The optical brightness is constant at the level given by the first line of equation (6) for about an hour (since for the fiducial parameters here $t_\gamma \sim 1$ s). Note that at 300 Mpc ($D_{28} = 10^{-1}$) the first line of (6) would be $m_v \simeq 14 + \cdots$. In this model, the self-absorption frequency (initially at $\sim 10^{13}$ Hz) evolves at first $\propto t^{-1/4}$, slower than ν_m, the two becoming equal at $t_{m,ab} \sim 4 \times 10^5 t_\gamma$ where

$\nu_{ab} \sim 3 \times 10^{11}$ Hz. Thereafter, the frequency $\nu_{ab} \propto t^{-11/14}$ and the peak of the spectrum separating the optically thick and thin regimes evolves as $F_{\nu_{ab}} \propto \nu_{ab}^{10/11}$ as long as the GRBR still expands relativistically (it reaches $\Gamma \sim 1$ after $t_{nr} \sim 10^8 t_\gamma$, about three years for $t_\gamma \sim 1$ s), and $F_{\nu_{ab}} \propto \nu_{ab}^{7/5}$ afterwards. As a result, the radio flux in the 100 MHz band is negligible, $F_R \lesssim 10^{-2} K D_{28}^{-2} \mu$Jy. (This refers to the usual *incoherent* self-absorbed synchrotron flux; the black-body upper limits used for this estimate could of course be violated by coherent emission mechanisms).

a2) A slightly more involved impulsive model considers both the reverse and the forward shock to be efficient radiators. An example of this occurs if for instance the ejecta has frozen-in magnetic fields, sufficiently strong to ensure radiation but not enough to dominate the dynamics (the FC model of RMP94, their Fig. 1a). At $t_\gamma \sim t_{dec}$ the reverse shock has achieved transrelativistic speed ($\bar{\Gamma}_r \sim 2$ respect to the ejecta, with $\kappa = 10^3$, $B' \sim 0.3$G and $\Gamma \sim \eta \sim 10^3$ in this numerical example). The ejecta electrons have $\gamma_{min} \sim 10^3$, giving an observed synchrotron peak at $\nu_m \sim 3 \times 10^{14} \sim 10^{15}$ Hz with fluence $S_\nu \sim 10^{-8} K D_{28}^{-2}$ erg cm$^{-2} \propto \nu^0$ above ν_m (or flux $F_\nu \propto \nu^{-1}$), where $K = E_{51} \theta_{-1}^{-2}$; then between 10^{18} and 3×10^{20} it has $S\nu \sim \nu^1$ (flux $F_\nu \sim \nu^0$), and $S_\nu \sim 10^{-6} K D_{28}^{-2}$ erg cm$^{-2} \propto \nu^0$ ($F_\nu \propto \nu^{-1}$) above 3×10^{20} Hz, the latter two corresponding to IC-scattered synchrotron by reverse shock electrons. We consider the evolution of the reverse shock (ejecta) region only, since it has stronger XR and O contributions than the forward blast wave. (The forward blast wave remnant might be naively expected to behave as the a1 case above, but being an IC component its contribution drops in time by two powers of γ faster than the synchrotron component). The shocked reverse gas is in pressure equilibrium with the gas forward of the CD, so it also moves with $\Gamma \sim t^{-3/8}$ and $r \propto t^{1/4}$ as does the CD. The ejecta frozen-in field behaves as $B' \propto r^{-2} \propto t^{-1/2}$. The comoving pressure on either side of the side of the CD evolves $\propto r^{-3}$ so the reverse gas, even though traversed by reflected pressure waves, cools in its rest frame with $T'_p \propto r^{-6/5}$ and the comoving density in the ejecta evolves as $n' \propto r^{-6/5} \propto t^{-9/20}$, the total number of particles in the ejecta remaining constant. The ejecta comoving radial width is $\Delta R' \propto r^{-1/5}$ and the ejecta column density is $n'.\Delta R' \propto r^{-2} \propto t^{-1/2}$. As the ejecta cool, any fresh acceleration of ejecta electrons can at most give $\gamma \propto \kappa T'_p \propto t^{-3/10}$, so the GRBR spectrum will be dominated by the adiabatic cooling of the electron energy acquired in the initial GRB shock heating, $\gamma \propto r^{-1} \propto t^{-1/4}$. The reverse peak $\nu_m \sim 10^{15} (t/t_\gamma)^{-11/8}$ Hz is produced by a comoving peak intensity $I'_{\nu_m} \propto n'_e B' \Delta R' \sim 10^{-3} (t/t_\gamma)^{-1}$. Therefore $F_{\nu_m} \propto t^2 \Gamma^5 I'_{\nu_m} \sim 10^{-23} K D_{28}^{-2} (t/t_\gamma)^{-7/8}$ evolves proportional to $\nu_m^{7/11}$. The self-absorption frequency initially is $\nu_{ab} \sim 10^{13} (t/t_\gamma)^{-3/8}$ Hz, and the absorption and synchrotron peak frequencies become equal at $\nu_{m,ab} \sim 10^{11}$ Hz after a time $t_{m,ab} \sim 10^3 t_\gamma$. Thereafter the peak of the self-absorbed flux occurs at a frequency $\nu_{ab} \sim 10^{11} (t/t_{m,ab})^{-57/56}$ where $F_{\nu_{ab}} \sim 3 \times 10^{-26} (\nu/\nu_{ab})^{69/57}$. The optical flux near 10^{15} Hz is $F_{opt} \sim 10^{-23} (t/t_\gamma)^{-9/4}$ for $t \geq t_\gamma$, both before and after $t_{m,ab}$. (In principle one might have expected somewhat later a phase of $F_{opt} \sim$ constant due to the $\propto \nu^0$ IC component coming into the optical range, but as mentioned above, the IC energy losses drop off in time much faster than the synchrotron losses, so this should not be important). The visual magnitude of the GRBR from

this reverse shock with frozen-in magnetic fields is therefore

$$m_v \simeq 9 - 2.5 \log K + 5 \log D_{28} + (45/8) \log(t/t_\gamma) \quad , \text{ for } t \gtrsim t_\gamma \ . \tag{6}$$

The incoherent flux in the 100 MHz radio band is maximum when the self-absorption peak passes through that frequency at the time $t_R \sim 10^6 t_\gamma$, giving $F_{\nu_R,max} \sim 1KD_{28}^{-2}\mu$Jy, which at 300 Mpc would be $\sim 0.1KD_{27}^{-2}$ mJy, still very low. Before the maximum of the radio flux (between $t_{m,ab}$ and t_R) the radio flux grows as $F_{\nu_R} \propto t^{21/16}$, and after t_R it decays as $F_{\nu_R} \sim t^{-9/4}$.

a3) A somewhat similar impulsive model also considers both reverse and forward shock emission, but differs from (a2) in the origin of the magnetic field, which is here assumed on both sides of the contact discontinuity to be built up by turbulent motions to some fraction of the thermal proton energy density. The GRB spectrum corresponds to the TC model of RMP94 (their Fig. 1b). In this example the field energy is a fraction $\lambda \sim 10^{-6}$ of equipartition, and all initial physical parameters (as well as the initial spectrum) are the same as in case a2) above; the optical peak is synchrotron from the reverse shock. However, the magnetic field evolves in time differently, $B'^2/8\pi$ maintaining itself roughly at a constant fraction λ of the thermal proton energy density $kn'T'_p \propto r^{-3} \propto t^{-3/4}$, so $B' \propto t^{-3/8}$ in the reverse shocked ejecta. Retracing the steps in a2) we now have $I'_{\nu_m} \propto t^{-7/8}$, $\nu_m \propto t^{-5/4}$, $F_{\nu_m} \propto t^{-3/4}$, or $F_{\nu_m} \propto \nu_m^{3/5}$ initially. Also $\nu_{ab} \propto t^{-11/16}$, and ν_m becomes coincident with ν_{ab} at $\nu_{m,ab} \sim 10^{10.5}$ Hz at the time $t_{m,ab} \sim 3 \times 10^3 t_\gamma$, where the peak value is $F_{\nu_{ab}} \sim 3 \times 10^{-26}$. After that time the peak of the self-absorbed spectrum moves down as $F_{\nu_{ab}} \propto \nu_{ab}^{59/53}$, with $\nu_{ab} \propto t^{-53/56}$. The optical flux around 10^{15} Hz is $F_{opt} \sim 10^{-23} KD_{28}^{-2}(t/t_\gamma)^{-2}$erg cm^{-2} s^{-1} Hz^{-1} both before and after $t_{m,ab}$, so the visual magnitude of the GRBR is

$$m_v \simeq 9 - 2.5 \log K + 5 \log D_{28} + 5 \log(t/t_\gamma) \quad , \text{ for } t \gtrsim t_\gamma \ . \tag{7}$$

The self-absorption peak comes into the 100 MHz radio range at $t_R \sim 3 \times 10^2 t_{m,ab} \sim 10^6 t_\gamma$ (a few weeks after the GRB, for fiducial parameters with $t_\gamma \sim 1$s), and the peak radio flux is $F_{\nu_R,max} \sim 10^{-2} KD_{28}^{-2}$ mJy, or more interestingly, $F_{\nu_R,max} \sim 1KD_{27}^{-2}$ mJy for a GRBR at 300 Mpc. Between $t_{m,ab}$ and t_R the radio flux grows as $F_{\nu_R} \propto t^{21/16}$, and decays as $F_{\nu_R} \sim t^{-2}$ after t_R.

4. GRBR Spectra from Wind Fireball Models

For wind models, GRB spectra have been discussed, e.g. by Mészáros & Rees, 1994 and Thompson, 1994, Thompson, 1996. The observed fluxes from the resulting GRBR will be given as before by equations (1) and (2), but there are significant differences from the impulsive case due to the smaller radii at which shocks occur, the different evolution dynamics (§2, b) and the different post-shock behavior of the physical quantities. Below we consider two particular examples of wind internal shock models.

b1) The simplest wind GRB spectrum would be one where the break around 10^{20}Hz ~ 0.5MeV is due to the synchrotron peak, e.g., a case resembling the (a1) impulsive spectra. We take as a specific

example (Papathanassiou & Mészáros, 1996), a case with $\eta = 10^2,\ t_w = 10^2$s, $t_{var} \sim 2 \times 10^{-2}$s, and at $r_{dis} \sim 6 \times 10^{12} t_{var,-2}\eta_2^2$cm the turbulently generated field is $B' \sim 10^6$ G and $\kappa \sim 10^3$ (internal shocks have $\Gamma_{rel} \sim 1$, so $\gamma_{min} \sim 10^3$ and $\nu_m \sim \eta\nu'_m \sim 10^{20}$ Hz. The total energy into $\theta \sim 10^{-1}\theta_{-1}$ is again $E = 10^{51}E_{51}$ erg spread over $t_w = 10^2 t_{w,2}$s. The GRB spectrum has the same shape and fluence as the impulsive case (a1), but the flux level is 10^{-2} because the duration is 10^2 longer in this example. We consider the GRBR regime for $r \gtrsim r_{imp} \sim 3 \times 10^{16} t_{w2}\eta_2^2$cm. However, in this type of model the comoving $t'_{sync} \sim 5 \times 10^{-7} B_6^{-2}\gamma_{3,min}^{-1} \ll t'_{ex}$, and the remnant undergoes essentially instantaneous cooling as soon as shocks stop heating the gas. This is characteristic of a wind model with a GRB break at 0.5 MeV ascribed to a synchrotron peak, since this requires high B' and γ. So in these cases we expect no significant emission from the GRBR after the gamma-ray flash, although there will be (as in a1) some contemporaneous optical and X-ray emission during the GRB itself, for $t < t_w$.

b2) Consider now GRB from wind internal shocks with a synchrotron peak at optical frequencies and an IC peak around 0.5 MeV. As a specific example (Papathanassiou & Mészáros, 1996) we take a model with $t_w \sim 10^2$s, $t_{var} \sim 2 \times 10^{-2}$s, $\kappa = 10^3$, $\eta = 10^2$, and at $r_{dis} \sim 6 \times 10^{12} t_{var,-2}\eta_2^2$cm we assume that magnetic fields build up by turbulent motions to a fraction $\lambda \sim 10^{-6.5}$ of the proton thermal energy, or $B' \sim 3$ G, which leads then to a GRB synchrotron optical peak at $\eta\nu'_m \sim 10^{15}$ Hz, and an IC peak near 10^{20}Hz ~ 0.5 MeV. The GRB fluence spectrum $\nu F_\nu t_w$ is the same as for the impulsive models b2and b3, and the flux has the same shape but is a factor 10^{-2} lower since here $t_w \sim 10^2$ s. In this case, the comoving synchrotron timescale $t'_{sy} \sim 5 \times 10^3 \gg t'_{ex}$, so the adiabatic approximation will be valid in the remnant, which retains a significant thermal energy content that is radiated away during the later expansion. During the GRB the initial optical peak at $\nu_m \sim 10^{15}$Hz has flux $F_{\nu_m} \sim 10^{-25} t_{w2}^{-1} K D_{28}^{-2}$ erg cm² s^{-1} Hz^{-1}. The comoving intensity is, from equation (1), $I'_{\nu_m} = F_{\nu_m} D^2/(c^2 t^2 \Gamma^5) \sim 10^{-4} K D_{28}^2 t_{w2}^{-1}\eta_2^{-5}$ and the self-absorption frequency is $\Gamma(I_{\nu'}c^2/[2\gamma m_e c^2])^{1/2} \sim 10^{12}$Hz. For the time scaling we use the properties of the wind in the impulsive $\Gamma \simeq$ constant phase (4), so the comoving synchrotron intensity scales as $I'_{\nu_m} \sim n'_e \Delta R' B' \propto t^{-4}$, the synchrotron peak frequency as $\nu_m \sim \Gamma B' \gamma^2 \propto t^{-4}$, and the observed flux at the synchrotron peak as $F_{\nu_m} \sim c^2 t^2 D^2 \Gamma^5 I'_{\nu_m} \propto t^{-2}$, so that the synchrotron peak moves down with peak frequency as $F_{\nu_m} \propto \nu_m^{1/2}$. The self-absorption frequency is $\nu_{ab} \propto \Gamma(I'_\nu/\gamma)^{1/2} \propto t^{-3/2}$, and the synchrotron maximum and the self-absorption frequencies coincide at $t_{m,ab} \sim 10^{6/5} t_w$ at $\nu_{m,ab} \sim 2 \times 10^{10}$ Hz, where the flux is $F_{\nu_{m,ab}} \sim 10^{-27}$. After that the self-absorbed peak of the spectrum moves down in frequency as $F_{nu_{ab}} \propto \nu_{ab}^{4/3}$. The optical flux as a function of time is given by $F_{opt} \sim F_{\nu_m}(\nu_m/10^{15}) \sim 10^{-25} K D_{28}^{-2}(t/t_w)^{-6}$. The corresponding GRBR visual magnitude is, as a function of time,

$$m_v \simeq 14 - 2.5\log K + 5\log D_{28} + 15\log(t/t_w) \qquad \text{, for} t > t_w \ , \tag{8}$$

where $K = E_{51}\theta_{-1}^{-2} t_{w2}^{-1}$. The initial magnitude (14, in this example) is constant for $t \lesssim t_w = 10^2$ s during the GRB, and it drops extremely fast in the GRBR phase afterwards. AT 300 Mpc, the initial magnitude is $m_v \sim 9$, dropping to 24 after $t \sim 10 t_w \sim 10^3$ s for these parameters. The radio flux in this model is very low, $F_R \sim 0.3 K D_{28}^{-2} \mu$Jy, or $0.03 K D_{28}^{-2}$ mJy at 300 Mpc, growing as t^3

before $t_R \sim 3 \times 10^2 t_w \sim 3 \times 10^4$s in this example, and dropping as t^{-6} afterwards.

5. Discussion and Observational Prospects

Gamma-ray burst remnants, or GRBR, should according to our calculations leave behind an afterglow at wavelengths longer than γ-rays, in particular at X-ray, optical, and in some cases also in the radio bands. The calculations discussed above apply both to spherically expanding configurations and to jet configurations, as long as the jet opening angle $\theta \gtrsim \Gamma^{-1}$. The adiabatic approximation made for the evolution of the remnant should be generally valid for times significantly longer than the gamma-ray burst duration. A wide variety of models, involving several unknown parameters, are compatible with the gamma-ray data. Observations in other bands offer the chance to narrow the range of options and refine existig models. The numerical examples discussed are illustrative of the possibilities, and should give a reasonable idea of the range of values that might be expected. There is greater reason for confidence in the scaling laws discussed, and in particular in the time dependence laws of the fluxes in different regimes for the various models, as these are based on simple physical arguments.

Omnidirectional, or at any rate large field-of-view X-ray detectors in space (such as HETE, Ricker, 1992) may be able to detect the simultaneous X-ray emission predicted for GRB (e.g. MRP94,Papathanassiou & Mészáros, 1996) as well as, for the brighter bursts, possibly the X-ray afterglow implied by our models discussed here, although surface areas higher than HETE's may be required to follow the remnant evolution.

The synchrotron radio fluxes from GRBR are expected to be very small, reaching their maximum value on timescales of weeks after the GRB outburst, which in the optimal cases (e.g. §2, b3) may be at most in the mJy range. The radio flux is expected to change before and after the maximum as power laws of the time which are characteristic of the models. Nonetheless, radio searches, even for very short timescale flashes, are worthwhile because we cannot rule out coherent emission behind relativistic shocks, which would of course permit brightness temperatures far higher than the usual self-absorption limit. (indeed, the intraday radio variations in AGN [Wagner, 1996] may exemplify coherent emission from shocks whose properties resemble those expected in GRBRs).

The optical detection of the GRB event itself is within the range of capabilities of modest size telescopes, but the problem is one of field of view, as typical BACODINE error boxes supplied within a minute of the GRB event are at least several degrees, and sometimes as much as ten degrees wide, and any significant improvement in location takes at least days. Thus detection of optical emission from the burst itself (rarely longer than minutes) is difficult. However the GRBR optical emission decays on longer timescales, typically hours, and for the initial magnitude levels implied by several of the models even at Gpc distances (e.g. $m_v \sim 9 - 14$, see §3 a2, a3, §4 b2), meter class telescopes equipped with CCD detectors may be able to cover a several square degree

wide field by doing rasters of ten minute observations. The advantage of such observations, if they can be repeated more than once over the same field, is that they would allow a determination of the optical flux time-decay exponent, which can help discriminate among models.

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